CLOSING PORES AND CRACKING: A WINDOW TO MARTIAN HISTORY FROM A SEISMIC WAVE SPEED DISCONTINUITY IN THE CRUST. S. Gyalay[1] and F. Nimmo[1], [1]University of California, Santa Cruz, CA 95064, USA (sgyalay@ucsc.edu)

Introduction: The InSight Mars lander discovered a discontinuity in seismic wave speed ~9±2 km below the surface [1, 2]. We have previously shown that after the generation of an initially porous crust by large impacts, high heat flow in early Martian history can viscously close the deepest pore spaces—offering an explanation for the jump in seismic wave speed with depth [3]. However, the increase in shear wave velocity is smaller than expected for a transition to solid rock and may be better characterized by reduced (but not zero) porosity, or by less-elongated pores [4]. Further, while a second discontinuity at 20±5 km depth could overlie the mantle or a third layer of crust [2], the latter is more likely [5]. We investigate how impacts may re-generate fractures after pores have been previously closed by viscous creep to generate a three-layer crust.

Closing Pores: Early Martian history was dominated by high heat flow due to high crustal heat production [6]. Thus, viscous creep would have been the dominant rock flow regime. Whether pore spaces close quickly (e.g., in 10 Myr) has a double exponential dependence on the temperature of the rock, leading to an abrupt closure of porosity below some depth.

If we assumed that a 10 km discontinuity in the Martian crust marked the base of the present fractured/porous layer, then the last significant pore-generating events occurred when the crust below InSight experienced a heat flow greater than 60 mW/m^2, indicating a time prior to 4 Ga [3].

However, if the crust deeper than 10 km is still porous, albeit less so, then either (1) the crust was cooler when pores closed, allowing for porosity deeper than 10 km to be cemented by an aquifer or (2) porosity did close deeper than 10 km and was later regenerated [4].

Cracking: As viscous pore closure at 4 Ga neatly coincides with the end of the era of large-basin-forming impacts [6], closure and later regeneration of porosity is an alluring explanation for the porosity transition. We focus on the regeneration of deep porosity by a likely candidate: impact-induced fractures.

Previous studies have examined the role of impacts in generating porosity [e.g. 8, 9], or even how prior porosity controls crater formation [e.g. 10-12]. The lunar megaregolith is a porous layer of the Moon's crust, which itself may be composed of layers with distinct porosities that have been inferred from gravity data for the Moon [e.g. 9, 13]. Similar processes may explain these thick, porous layers within the Martian crust.

To avoid computational-intensive simulations, we elected to use empirically derived formulae for the propagation of stress and cracks from a given impact, as explored in [14 and references therein]. We outline the critical steps below and use them to explore what magnitude of impacts are necessary to regenerate porosity deeper than 10 km below the Martian surface.

As a bolide impacts a planetary surface, it forms a region of constant pressure, an isobaric core. This characteristic shock σ_0 is approximately ρU^2, where ρ is the projectile density and U its impact velocity (exact equations in [15]). This provides a slight overestimate as it ignores near-surface effects.

The isobaric core has a radius up to a few times the radius of the impactor R_0. Outside of the isobaric core, the stress σ suffered by the crust some distance R from the impact site is

$$\sigma = \sigma_0 \left(\frac{R}{R_0}\right)^{-n}, \qquad (1)$$

where n depends on the velocity of the impactor [e.g. 14]. We have found the impactor's size matters more than its composition. [16] propose $n = 0.625 \log_{10} U + 1.25$, where U is the impactor speed in km/s. [17] instead propose $n = 2.61\, log_{10} U - 1.84$, for an impactor of radius 0.2-10 km at 10-80 km/s into a silicate target. We test both in our simple model.

To form a crack within the crust from an impact, the stress from the dilational waves must overcome some intrinsic strength of the crust [14]. The radial stress σ perpendicular to the shock front is compression, while the circumferential stress σ_θ is tension. Radial cracks from circumferential tension form more easily than concentric cracks because the tensile strength of rock is lower than its compressive strength. To form a radial crack, we need the circumferential stress from the impact, $\sigma_\theta = \sigma/3$. This must then overcome the sum of the rock's critical dynamical tensile strength P_C and the overburden pressure P.

$$\sigma_\theta \geq P_C + P. \qquad (2)$$

We adopt a maximum tensile strength of 0.1 MPa as used by [10] when simulating impacts into a layer of regolith atop a layer of competent rock. Neither [16] nor [17]'s stress propagation relations are stated to work on porous regolith, but we hope they provide at least an order of magnitude understanding. Fig. 1 displays the depth of cracking directly below an impact.

Finally, we calculate the distance on the surface from the impact site where cracks can propagate to depth 10 km or below. We solve for R that satisfies Eqs. 1 and 2 for the overburden pressure at 10 km depth and use the Pythagorean theorem to find the surface distance assuming a right triangle with one side 10 km and the hypotenuse R (Fig. 2).

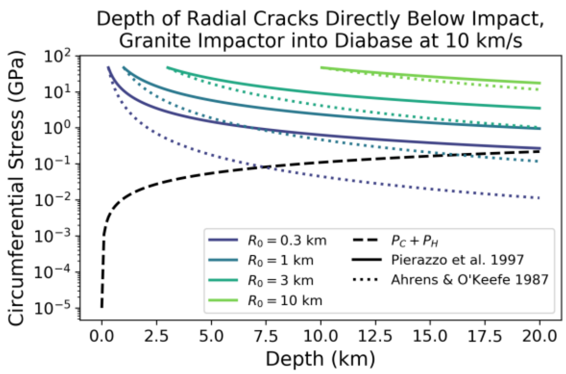

Figure 1: Circumferential stress directly below an impact for a range of impactor sizes, using n from Ahrens & O'Keefe [16] vs. Pierazzo et al. [17]. Tensile strength and overburden pressure of rock at a given depth must be overcome by stress to crack.

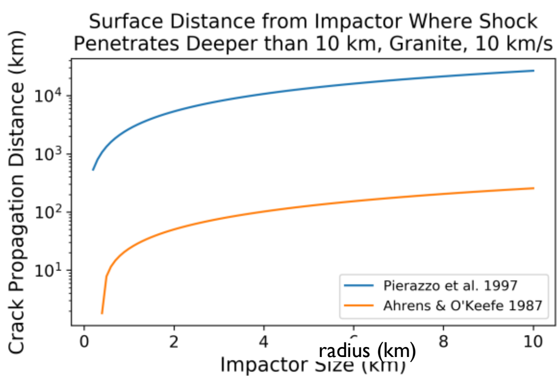

Figure 2: Distance on the surface from an impactor where cracks are formed below 10 km using n from Ahrens & O'Keefe [16] vs. Pierazzo et al. [17].

If the radius of a crater scales as roughly 10x the radius of an impactor, then we would expect a 10 km wide crater within a few 10s of km (to 1000s if [17] is to be believed) away from InSight to generate porosity where it may have already closed deeper than 10 km depth. There are at least four 8-10 km wide craters within 80 km of InSight. We may instead expect a 100 km wide crater 100-10,000 km away. Craters Gale, Knobel, and Robert Sharp are all greater than 100 km wide and are within 700 km of InSight (Fig. 3).

Discussion: Porosity deeper than 10 km may have closed viscously due to how hot early Mars was. But with approximations of impact shock and crack propagation models, we have found that impacts can (re)generate deep crustal porosity. This may allow for a two-layer megaregolith of differing porosities, consistent with [4]'s findings. Alternatively, some original porous layer may have been overlain by kilometers of lava or sediments [3, 5], which subsequent impacts ensured were porous.

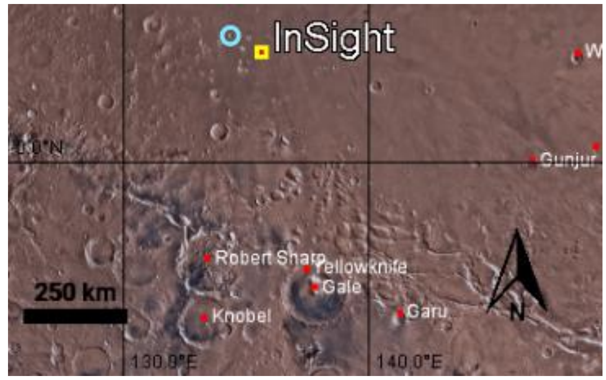

Figure 3: Craters near the InSight landing site (yellow box). The light blue circle marks the location of the nearest 10 km crater, ~80 km away.

The potential far reach of pore generation from even smaller craters does beg the question of how the spherical geometry of Mars will affect the results, so in the future we will take that into account. Another step we can take to refine our assumptions and test our model is to investigate how crack propagation from impacts holds in porous regolith or in a transition from porous to compact rock, similar to what is simulated in [10]. Finally, we can also run a Monte-Carlo simulation that calculates how deep porosity may extend after pore closure and subsequent random impacts upon Mars.

Acknowledgments: We thank Mark Wieczorek for insightful comments. FN is supported by NASA grant 80NSSC18K1627.

References: [1] Lognonné et al. (2020), *Nature Geosci. 13*, 213. [2] Knapmeyer-Endrun et al. (2021), *Science 373*(6553), 438. [3] Gyalay et al. (2020), *GRL 47*(16). [4] Manga & Wright (2021), *GRL 48*(8). [5] Kim et al. (2021), *JGR:Planets 126*(11). [6] Hahn et al. (2011), *GRL 38*(14). [7] Bottke & Andrews-Hanna (2017), *Nature Geosci. 10*, 344. [8] Collins (2014), *JGR:Planets 119*(12), 2600. [9] Soderblom et al. (2015), *GRL 42*(17), 6939. [10] Senft & Stewart (2007), *JGR:Planets 112*(E11). [11] Milbury et al. (2015), *GRL 42*(22), 9711. [12] Johnson et al. (2021), *Icarus 366*. [13] Izquierdo et al. (2021), *GRL 48*(22). [14] Ai & Ahrens (2004), *Meteoritics & Planet. Sci. 39*(2), 233. [15] Melosh (1989), *Impact Cratering*, Oxford Uni. Press. [16] Ahrens & O'Keefe (1987), *Int. J. of Impact Eng. 5*(1-4), 13. [17] Pierazzo et al. (1997), *Icarus 127*(2), 408.